Towards a Formal Definition of Timing Predictability

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Outline

1 Motivation

2 Predictability
- Disambiguation
- Definitions

3 Component Model
- Individual Components
- Composition

4 Summary & Questions

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Motivation

- Complexity of embedded systems increases
- They become more and more “unpredictable”

- With current methods
  - computation of WCET bounds will become infeasible or
  - computed bounds will be useless

⇒ Need better analyses or more predictable systems

Also true for schedulability and response-time analysis?

Motivation II

- To design predictable systems one should know what predictability means, right!?
- People mean different things when saying “predictability”
- Criteria for predictability are mostly
  - intuitive
  - case-based
  - phenomenological, symptom-based

Examples on the CPU-Level

Predictability:	better	worse
pipeline	in order	out of order
branch prediction	static	dynamic
cache organization	private	shared caches
replacement policy	LRU	PLRU

- This is based on intuition and experience
- Is there an underlying principle?

Goals

- Disambiguate meanings and clarify notions
- Derive definitions/criteria that are
  - formal
  - uniformly applicable
  - reason-based

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What is Predictability?

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Oxford Dictionary

predictable: adjective, able to be predicted
to predict: verb, state that (a specified event) will happen in the future

- Predictability is a property of a system
- Definition should not depend on specific analysis techniques

Proposition

The notion of predictability should capture if, and how precise,
a property can be predicted by any analysis.

Alternative Point of View

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- Would like to consider analysis costs
- predictable: able to be predicted with reasonable effort

Alternative proposition

The notion of predictability should capture if, and how precise, a property can be predicted by any efficient analysis

- How to argue about all efficient analyses?
- What is efficient?
- Complicates matters even more

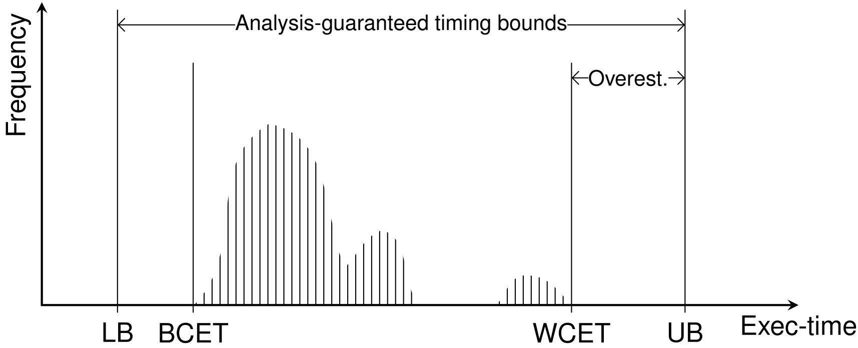
Non-determinism

- In deterministic systems one can predict properties exactly
- However, there is non-determinism
- The amount of non-determinism determines the quality of a prediction

$\Rightarrow$ Determine and distinguish sources of non-determinism

- Next: Property “Time”

Notions in Timing Analysis



- BCET/WCET: Best- and worst-case execution time
- LB/UB: Lower and upper bound

Disambiguation I

- No analysis can do better than [BCET, WCET]
- This interval limits the precision of predictions

$\Rightarrow$ Intrinsic (inherent) / Predictability

- An efficient analysis has to abstract and can only predict [LB, UB]

$\Rightarrow$ Extrinsic (ascribed to analysis) / Predictability'

Non-determinism in Execution-Times

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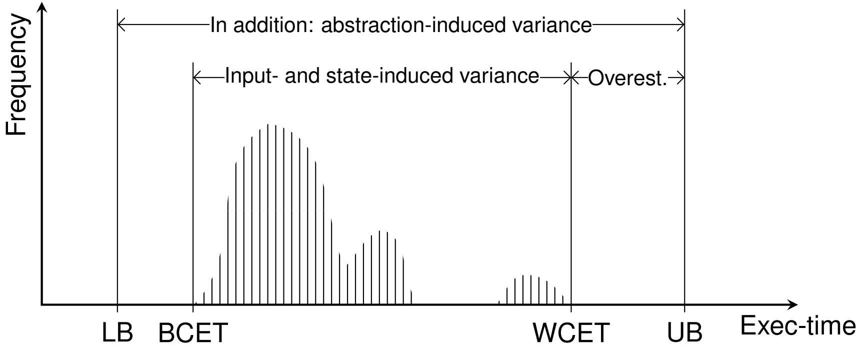
Execution time of a program *p* on a given system depends on

- the system input
- the initial hardware state



Disambiguation II

- Uncertainty about state shows up at the “beginning”
- Implies set of possible initial hardware states

- Uncertainty about input shows up during execution
- Implies set of possible transitions

Proposition

State-induced predictability	variance due to different initial states
Input-induced predictability	variance due to different inputs

State, Input, Execution Time

- Let Q denote the set of all system states
- System is input-deterministic

- Let I denote the set of all inputs
- e.g. streams of sensor values

- Let $T_p(q, i)$ be the execution time of program p, starting in hardware state $q \in Q$ with input $i \in I$.

Predictability

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Definition: Predictability

$$\mathrm{Pr}_p(Q, I) := \min_{q_1, q_2 \in Q} \min_{i_1, i_2 \in I} \frac{T_p(q_1, i_1)}{T_p(q_2, i_2)}$$

- Captures maximal variance in execution time
- Measure is within [0..1]
- 1 means perfectly predictable (= Berkeley-repeatable?)

State-induced and Input-induced Predictability

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Definition: State-induced Predictability

$$\mathrm{SIPr}_p(Q, I) := \min_{q_1, q_2 \in Q} \min_{i \in I} \frac{T_p(q_1, i)}{T_p(q_2, i)}$$

Definition: Input-induced Predictability

$$\mathrm{IIPr}_p(Q, I) := \min_{q \in Q} \min_{i_1, i_2 \in I} \frac{T_p(q, i_1)}{T_p(q, i_2)}$$

- Predictability comprises state- and input-induced predictability
- $\mathrm{SIPr}_p \cdot \mathrm{IIPr}_p \leq Pr_p$

Problems With These Definitions

- Definitions based on observable behavior (time)
- But we want to capture its reasons

⇒ What is the reason for the variance?

- Definitions depend on a program
- But predictability is system property

⇒ How to quantify over all programs?

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Components

- System consists of connected components
- Each component has
  - component state
  - component input
- State of all components determines system state

What is the reason for the variance?

- Variance should appear in individual components
- Variance in components “somehow” adds up

Goal: Come up with model that is compositional wrt. predictability

1. Characterize variance/predictability of each component
2. Use compositionality to deduce system predictability

How to quantify over all programs?

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- Program can be seen as part of system input
- Anyway, $\left\{\begin{array}{l}\text{Program}\\ \text{System input}\\ \text{System state}\end{array}\right\}$ induce component input
- Over-approximate component input
- For now, consider all component inputs

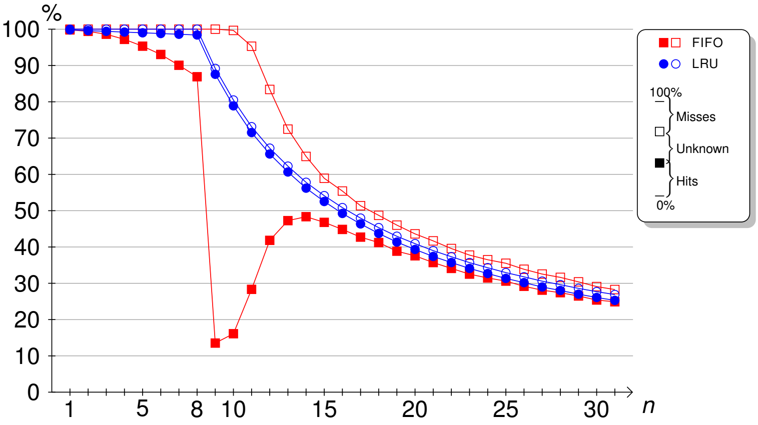
Example: Caches

- State: cached blocks and status of replacement algorithm
- Input: sequences of accesses
- Output: $(\mathit{Hit}|\mathit{Miss})^*$

- Characterize predictability

State-induced variance

for different classes of inputs



From Percentages to Timing Variance

- Graph showed events
- Events can be associated with times
- Times do not simply add up
- E.g. penalties might mask each other out

Composition

- Which information do we need about components to achieve compositionality?
- That is, how to abstract?
- Certainly not by a graph like the previous one
- What sizes are appropriate to describe components?
- Input-output relation?

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- Predictability is variance due to inherent system properties
- Difficult to restrict to “efficient” analysis

- How do we achieve compositionality wrt. predictability?
- What information do we need about components to achieve this?
- Likely, I am biased to WCET determination:
  can you concretize my terms into your domain?